

SIMULATING DISK GALAXIES AND INTERACTIONS IN MILGROMIAN DYNAMICS

I. THIES¹, P. KROUPA¹, and B. FAMAHEY²

¹*Helmholtz-Institut für Strahlen- und Kernphysik, D-53115 Bonn*

E-mail ithies@astro.uni-bonn.de

E-mail pavel@astro.uni-bonn.de

²*Observatoire astronomique de Strasbourg, F-67000 Strasbourg, France*

E-mail benoit.famaey@astro.unistra.fr

Abstract. Since its publication 1983, Milgromian dynamics (aka MOND) has been very successful in modeling the gravitational potential of galaxies from baryonic matter alone. However, the dynamical modeling has long been an unsolved issue. In particular, the setup of a stable galaxy for Milgromian N-body calculations has been a major challenge. Here, we show a way to set up disc galaxies in MOND for calculations in the PHANTOM OF RAMSES (PoR) code by Lügghausen (2015) and Teyssier (2002). The method is done by solving the QUMOND Poisson equations based on a baryonic and a phantom dark matter component. The resulting galaxy models are stable after a brief settling period for a large mass and size range. Simulations of single galaxies as well as colliding galaxies are shown.

1. INTRODUCTION

Since its invention by Milgrom (1983) modified Newtonian dynamics (MOND) has been successfully implemented in numerical codes for simulations of galaxies and galaxy systems (see Famaey & McGaugh 2012 for a review). The most recent implementation of MOND is the PHANTOM OF RAMSES (PoR) code by Lügghausen et al. (2015), based on RAMSES by Teyssier (2002). In this contribution the setup of stable disk galaxies is described and applied to the simulation of interacting galaxies. For the first time, the rotation curve of a galaxy in MOND is calculated.

2. NUMERICAL METHODS

The setup of an N-body system in MOND is not as straight-forward as in Newtonian dynamics since the Milgromian gravitation depends on the Newtonian acceleration and thus two iterating Poisson equations need to be solved. The first step is the setup of the desired density profile, $\rho_b(\mathbf{x})$. In this contribution exponential disk profiles with a finite truncation radius are used. Next the Newtonian Poisson equation is solved to obtain the Newtonian accelerations, $\nabla\phi$. Using the quasi-linear formulation of MOND (QUMOND, Milgrom 2010), in which the Milgromian modification term of

gravity is represented by a “phantom dark matter” density distribution, the combined Newtonian and Milgromian Poisson equation can be written as

$$\nabla^2\Phi(\mathbf{x}) = 4\pi G\rho_b(\mathbf{x}) + \nabla \cdot [\nu (|\nabla\phi|/a_0) \nabla\phi(\mathbf{x})] \quad (1)$$

or

$$\nabla^2\Phi(\mathbf{x}) = 4\pi G (\rho_b(\mathbf{x}) + \rho_{ph}(\mathbf{x})) . \quad (2)$$

Here, $\rho_b(\mathbf{x})$ is the density distribution of the baryonic (real) matter, and $\rho_{ph}(\mathbf{x})$ describes the distribution of the phantom dark matter. By solving the QUMOND Poisson equation the accelerations and thus the circular velocities of particles in a stable disk galaxy can be obtained.

The setup is done via the MKGALAXY script by McMillan & Dehnen (2007), modified by Lügghausen in 2015 for MOND. Besides an installation of PoR the script requires the NEMO stellar dynamics library and the PNBODY Python library for N-body calculations. Gas initial conditions require to patch the PoR code by editing the CONDINIT subroutine accordingly. This has been done by I. Thies in 2015 based on the MERGER patch by D. Chapon in 2010 which is readily available in the RAMSES installation. The new patch is currently available on request from the author.

3. Results

3. 1. STABLE ISOLATED GALAXIES

A disk galaxy with a stellar mass of $80 \cdot 10^9 M_\odot$ and gas mass of $10 \cdot 10^9 M_\odot$ is set with an exponential radial profile and a scale radius of 2 kpc. There is no initial bulge.

In the initial configuration as well as after 5 Gyr the rotation curves are calculated as the circular velocities from the radial accelerations of the particles. In agreement with observations the rotation curves are relatively flat in the outer parts, as can be seen in Fig. 2.

3. 2. INTERACTING GALAXIES

A pair of galaxies, each with the parameters described above, has been set for a grazing collision. As can be seen in Fig. 3, the interaction causes prominent tidal arms immediately after collision. The galaxy cores then orbit each other several times before eventually merging after about 5.5 Gyr. After about 5 Gyr satellite galaxies are visible as gaseous clumps orbiting in the plane of the encounter orbit.

In Fig. 4 the stellar component of the interacting galaxies is plotted. More precisely, the stars which formed since the begin of the simulation are shown in order to emphasise the regions of star formation. As in the gas plot at timestamp 5200 Myr a few satellite galaxies are visible around the almost merged original disk galaxies. It has to be noted that due to the resolution limits of both the gas mesh and the star-representing particles only the most massive satellites can form and remain stable. In higher resolution simulations more satellites of lower masses are expected to form.

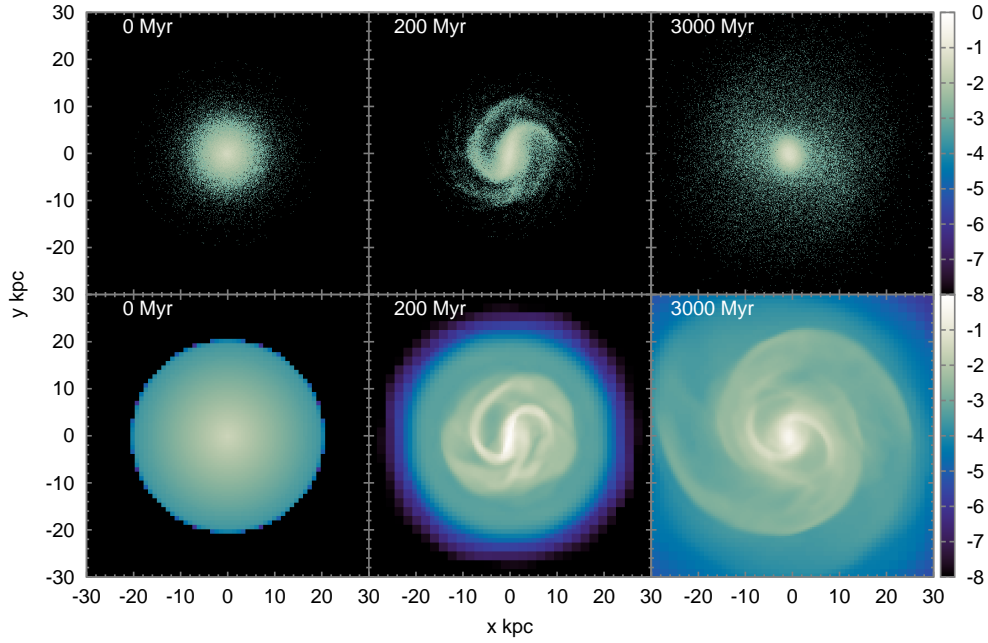


Figure 1: Snapshots of a disk galaxy model at 0, 200 and 3000 Myr after setup. The upper row shows the stellar component while the lower row depicts the gas projected density. The colour coding refers to $\log(\Sigma/[10^9 M_\odot \text{ kpc}^{-2}])$. Strong spiral arms form within the first few 100 Myr and thermalise after a few Gyr with only weak spiral features remaining in the stellar component. The gas component has spread significantly but still shows prominent spiral features after 3 Gyr, when the galaxy has settled completely and does not change much more with time.

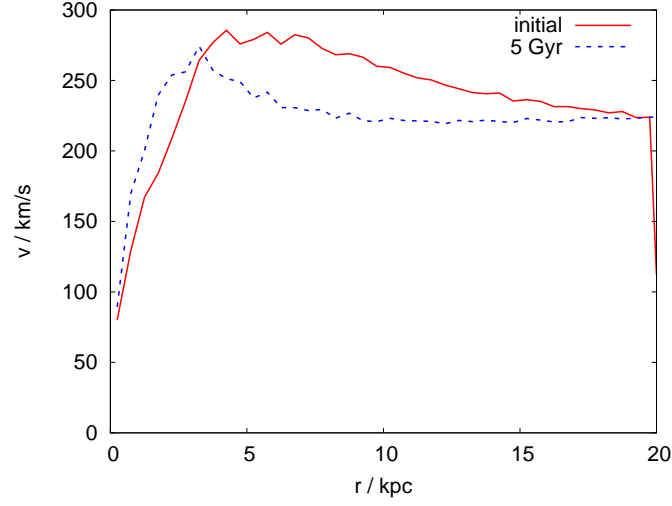


Figure 2: The rotation curve at the beginning and after 5 Gyr. In agreement with observations the rotation curves are relatively flat in the outer parts.

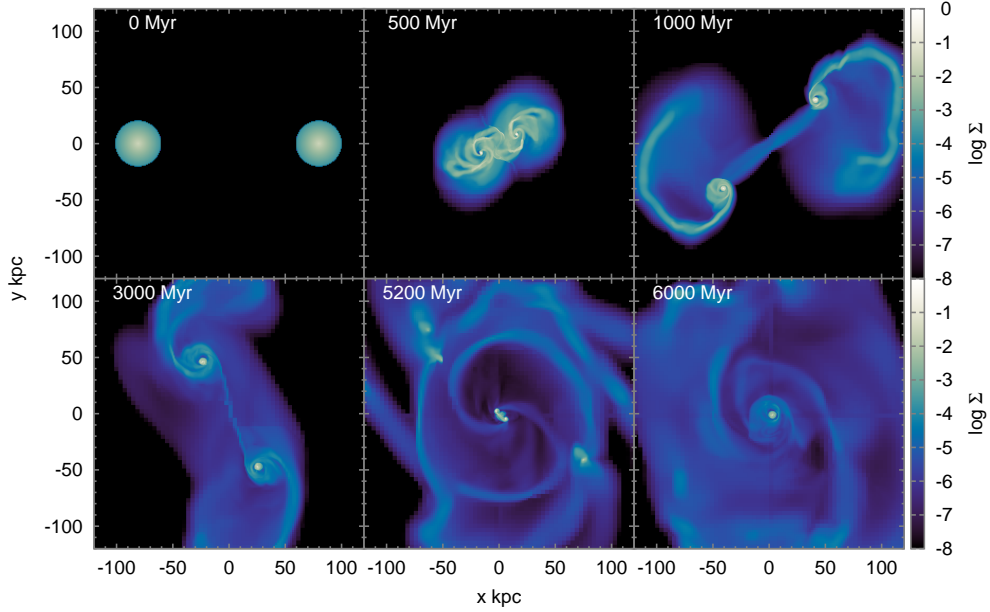


Figure 3: Snapshots of the gas component of two interacting galaxies. Note that it takes about 5500 Myr, measured from the time of collision at timestamp 500 Myr, for the galaxies to merge. This corresponds to six perigalactic passages. Note the three substantial tidal dwarf galaxies in the lower central panel (5200 Myr)

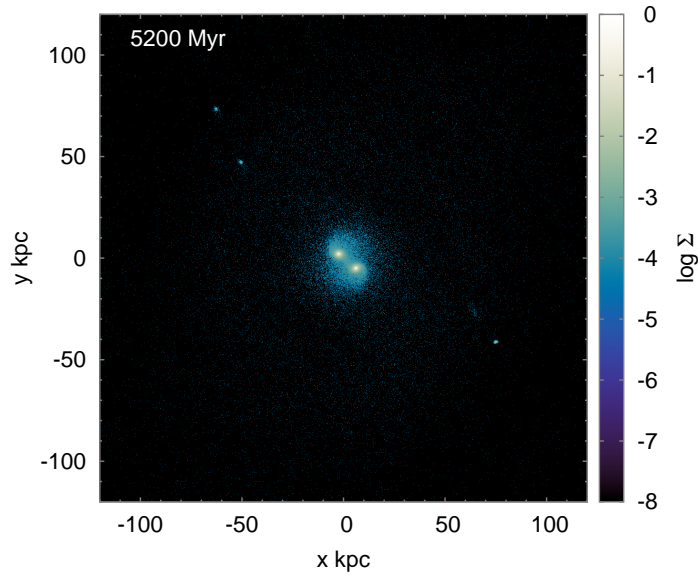


Figure 4: Snapshot of the stellar component of two interacting galaxies at timestamp 5200 Myr. The satellites correspond to the gas clumps in the lower middle panel in Fig. 3.

4. Summary and future perspectives

In this contribution the method of setting up stable disk galaxies in Milgromian dynamics (MOND) has been introduced. For the first time, the rotation curve of such a galaxy model, which qualitatively matches observed rotation curves of existing disk galaxies, has been shown. Furthermore, it has been demonstrated that interacting galaxies tend to merge relatively late (here after six perigalactic passages within about 6 Gyr) in contradiction to the Λ CDM model which predicts quick mergers due to the dynamical friction of the dark matter halos (Privon, Barnes et al. 2013). In addition, the formation of tidal dwarf satellite galaxies in MOND has been demonstrated.

The ongoing project aims to perform computations with highly increased resolution in order to reproduce satellite systems like those of the Milky Way Galaxy and the Andromeda galaxy. Furthermore, the rotation curves of such satellites are to be calculated. The predictions of these models may then be tested with observations.

5. Acknowledgement

I. Thies and P. Kroupa wish to thank the BELISSIMA team for the invitation.

References

- Famaey, B., McGaugh, S. : 2012, *Liv. Rev. Rel.* **15**, 10.
 Lüghausen, F., Famaey, B., Kroupa, P. : 2015, *Can. J. Phys.* **93**, 232.
 McMillan, P.J., Dehnen, W. : 2007, *MNRAS* **378**, 541.

- Milgrom, M. : 1983, *Astrophys. J.* **270**, 365.
Milgrom, M. : 2010, *MNRAS* **403**, 886
Privon, G.C., Barnes, J.E., Evans, A.S. et al. : 2013, *Astrophys. J.* **771**, 120.
Teyssier, R. : 2002, *Astron. Astrophys.* **385**, 337.